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FINAL SUMMARY REPORT
A DESCRIPTIVE MODEL FOR DETERMINING OPTIMAL
HUMAN PERFORMANCE IN SYSTEMS

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SERENDIPITY ASSOCIATES
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for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

RESEARCH REPORT SERIES

Prepared under Contract NAS 2-2955

for

A DESCRIPTIVE MODEL FOR DETERMINING OPTIMAL
HUMAN PERFORMANCE IN SYSTEMS

Research Report I

PART A

A SIMPLE MODEL OF A MAN-MACHINE DEVELOPMENT CYCLE

PART B

A SIMPLE CALCULUS FOR DISCRETE SYSTEMS

Research Report II

PART A

SYSTEM DEVELOPMENT ACTIVITIES CONCERNED WITH
PUTTING MAN IN AN AEROSPACE SYSTEM

PART B

DEVELOPMENT OF MAN-MACHINE SYSTEMS:
Some Concepts and Guidelines

Research Report III

AN APPROACH FOR DETERMINING THE OPTIMAL ROLE OF MAN
AND ALLOCATION OF FUNCTIONS IN AN AEROSPACE SYSTEM

Final Summary Report

A DESCRIPTIVE MODEL FOR DETERMINING OPTIMAL
HUMAN PERFORMANCE IN SYSTEMS



FOREWORD

This report describes a study carried out by Serendipity Associates under contract NAS 2-2955 for the Biotechnology Division of the Ames Research Center of the NASA. The purposes of this report are: to summarize the objectives of the study as a whole, to describe the method employed to carry out the study, and to present recommendations for further work. This study report contains a summary of results, but it is not intended as a technical report; three research reports present the technical products of the study. These research reports are identified on the preceding page; they will be described and interrelated in this report.

This effort was greatly enhanced through the interest and support of the technical monitor, Mr. Charles Kubokawa of the Biotechnology Division at Ames Research Center.

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I. OBJECTIVES OF THE STUDY

The successful operation of every spacecraft and of every aircraft requires that essential functions be carried out by men. Even when the flight segment of the system is unmanned, human performance is required in launching and recovering the flight segment. Long before most other industries became aware of the importance of man in the operation of complex systems, the aerospace industry began to concern itself with the problems of man in aircraft systems. Perhaps the aerospace industry was motivated by the high cost of system failure, both in terms of dollars and human life, but whatever the motivation, the aerospace industry has been a leader in the development of system personnel selection techniques, system operator training, and human engineering, all to the end of achieving superior aircraft system reliability. The development of technology has now brought to the fore another problem which relates to man in aerospace systems — a problem which requires once more that the aerospace industry invest in study to help find general solutions.

Since the decade of the forties when human factors began to be accepted as of significant importance, hardware technology has flourished and its fruits are now so abundant that an aerospace system designer frequently has options to implement critical aerospace system functions by means of hardware or by means of human performance. While there are still instances where the use of human performance is mandatory, the many instances where it is not call for decisions to be made. The decisions called for go beyond the scope of personnel selection, personnel training, human engineering, and all of the other established specializations that are concerned with man in an aerospace system. Basically what is required is that decisions be made in the course of aerospace system development which relate to two questions: (1) should man be included in the system at all, and (2) if he be included, what functions should be implemented by him?

The overall focus of the study reported here was upon the decision processes necessary to answer these two basic questions in the process of developing an aerospace system. The objective was to develop materials that would assist aerospace system designers.

The very posing of the question "Should man be included in this system to implement system functions?" carries with it the connotation that the question is not to be answered simply by flipping a coin. There is an implication that the "right" decision should be made — that man should be included in the system if it is better to implement the system that way than to implement it without man. What is lacking is a criterion, a basis for deciding whether or not a given decision is a good one. The second question carries with it the same sort of connotation. Thus, to ask "What basic functions should be implemented by man in this system?" is to imply that there is an optimal allocation of functions and that we desire some criterion by which to decide what is optimal and what is not. Therefore, this study was concerned with identifying and justifying criteria to be employed in answering these questions, as well as with identifying the more mechanical aspects of finding answers.

The Zeitgeist, in which cost-effectiveness has become a key word, provided an important background for the selection of criteria by which good answers to these questions might be recognized. Thus, as progress in technology has inevitably led the aerospace industry to concern over the basic design decisions involving the use of men in aerospace systems, there have been parallel developments in another area that have yielded concepts which are of basic importance to these decision questions. The complex systems which the new technology enables us to build are frequently very costly. In fact, sometimes to build and operate one of the new systems requires a significant portion of the total resources available to us as a nation. Because the impact of such high costs in terms of resources cannot go unnoticed, economic concepts have recently found an accepting audience in the Department of Defense and in other major government agencies. It has been simply a case of need creating an audience for proffered solutions. One important result of the new introduction of economic thought into the prosecution of major system development programs has been to familiarize managers of complex system development programs with the concept of optimal use of resources. These days we are less likely to think exclusively about building a system that will do a job, and we are more likely to think about balancing the resources needed to build and operate the system against what the system can do for us as compared with other resources used. In the case of aerospace

systems, decisions whether or not to include man in the system, and decisions with respect to what man will do in the system if he be included, impact both the cost of development and the usefulness of the system that is finally built. Therefore, the Zeitgeist favors the intersection of concern with the decision problems and ideas about system optimization in terms of cost and quality as criteria for resolving the decision problem.

In this study, it was accepted that the basic criterion to be used in deciding how to implement a system is cost and quality jointly considered.¹ Moreover, it is the cost and quality of the total system required to solve a given problem that is of interest; the idea does not permit a separate and independent assessment of a part of a system in cost and quality terms. Therefore, if we wish to concern ourselves with the optimal allocation of performance to man in the development of an aerospace system, we must be prepared to talk about the aerospace system as a whole, and not simply about the man-performance in it. And just as we must talk about the cost and quality of the aerospace system as a whole, so must we concern ourselves with the whole development cycle necessary to produce it, so that we may see the decision processes in question in the context of a complete development cycle for producing a complete aerospace system. What is called for is a way of designing and controlling the process of developing aerospace systems that provides for the consideration of man as a means of system implementation and which provides for his inclusion in the system to the end that the decisions made will result in a system of the desired quality at an acceptable cost.

The study reported here is therefore concerned with the design and control of the aerospace system development process. The basic method selected for presenting information about the development process was to employ an aerospace system development cycle model. At the heart of the study there was the attempt to generate and rationalize a development cycle model that could be used by development cycle managers to provide for the proper inclusion of

¹ We use the word quality here to refer to the idea which is also sometimes connoted by benefit, effectiveness, utility, and the like, as used to convey the concept of system "goodness."

the activities necessary to achieve a system that would employ man in an optimal way. The criterion against which the development cycle model was prepared was an overall system assessment in terms of cost and quality with general regard for the manner in which man is to be employed in the system. To provide for the development of an aerospace system that will not suffer in quality or cost because of the improper consideration of man in the system, the model that was developed and which is reported in Report IA is one which specifically identifies three categories of activities:

1. Activities deliberately woven into the early phases of system development which are designed to enable determination of whether or not man should have a role either in the flight segment or in the ground segment of an aerospace system.
2. Activities carefully related to parallel hardware development activities and focused upon determining the specific operator and maintenance tasks to be carried out by man in an aerospace system (assuming that he has a role).
3. Activities to provide for fabricating man (selection and training) and man-related things which must be delivered as parts of a total operational aerospace system in a manner that will assure capability and reliability of man and man-related products.

Since the development cycle model is the vehicle which relates man-focused activities in system development to overall development cycle criteria, the model presented in Report IA was a central point of departure for all of the study work, and the report of the model is the anchor point of the research report series. A brief summary of this report, and of the other reports in the series, is presented in the following section of this study report. Research Report IA will be of interest to those who must take part in the overall design of an aerospace system development cycle. The report provides basic information and concepts which should provide a useful point of departure for carrying out development cycle design. The report will also be of interest to anyone who is engaged in the study of development cycle strategy per se. Such a reader will also be interested in Report IB which presents a simple calculus

for discrete systems that is an appropriate language for describing development cycles and development cycle strategy. Research Report IB will probably not be of interest to someone who is not in some sense a student in the special area of development cycle processes.

The model which is presented in Report IA is an appropriate document to consult if one is concerned with the overall development cycle design problems. Detail with respect to the man-related development cycle activities is presented in Report IIA. The second report will therefore be of interest to managers concerned with the design and control of those aspects of the aerospace system development cycle process that are specifically concerned with man-related problems. When used for the purpose of providing information about the design of man-related activities in development, the user of the report will find that Research Report IA will also be useful.

Whereas Reports IA and IIA take an overall look at the development process, there is need for a report specifically concerned with the two questions, "Does man have a role?" and "What is the optimal use of man, if he has a role?" Specialists concerned specifically with these two questions should consult Report III. This report takes a look at the development process specifically for the purpose of answering these questions. The report will be useful to anyone who must plan a strategy in detail for answering these two questions in a specific aerospace system development cycle. It will also be useful to anyone who must carry out the actual work in development germane to allocation of functions to man. For such users the report is amplified by appendices that present important data.

Reports IA, IB, IIA, and III use a special language to provide for a precise description of the aerospace system development process. This language is described in Report IA for the general reader. That part of the language which relates to the calculus is, of course, presented in detail in Report IB. Many readers will find that terms commonly used in the human factors and biotechnological areas of specialization are simply not employed in these reports. Use of many of the common terms has been avoided because of the ambiguity associated with ordinary usage. Report IIB is for readers who would like to relate the vernacular to the special usage. It considers the terms and concepts

in common use that are germane to the topic of the study and presents an everyday interpretation of them. It also shows how they are related to the special language of the report series. Of all of the research reports, Report IIB is thus the least closely tied to the development cycle model which is the core of the study.

II. SUMMARY OF RESEARCH REPORTS

The purposes of this section are to explain the individual goals of each of the five parts (packaged in three reports) in the study series and to characterize the content of each.

As stated in the previous section, the overall objectives of the study were to provide tools to aid in management decisions germane to the development of complex aerospace systems to the end that man be employed in an optimal way. Each of the five parts is focused upon a particular area of concern to enable the necessary decision-making, planning, and execution efforts to be carried out. The five parts of the study are packaged in three reports with Reports I and II containing two parts each, identified as A and B respectively. Part A of Report I is identified as Report IA; Part B of Report I is identified as Report IB, etc. The five parts of the three reports are discussed in order, i. e., IA, IB, IIA, IIB and III.

A very brief review of the reports will be useful as an introduction. Report IA is entitled A Simple Model of a Man-Machine Development Cycle. It describes the major efforts necessary to develop a complex aerospace system. Report IB, entitled A Simple Calculus for Discrete Systems contributes a public language for talking about development cycles. It provides a foundation upon which the description of future development cycles may be based. Further, it provides the rationale for, and a precise definition of, some of the basic terms and notations used in the development and expression of the simple model explained in Report IA. Report IIA is entitled System Development Activities Concerned with Putting Man in an Aerospace System. It describes each of the biotechnological functions which should be carried out during a development cycle to yield the system personnel and supporting equipment necessary to man the operational aerospace system. This report fractionates in further detail those biotechnological functions first identified in the simple model in Report IA. Report IIB—Development of Man-Machine Systems: Some Concepts and Guidelines—is an attempt to relate selected terms generated by necessity for precise communication within the Research Reports, to the common vernacular of the biotechnology and system engineering community. Hence, this report

enables the reader to understand the basic differences and similarities between the vernacular and the special language introduced in Reports IA and IB. Report III is called An Approach for Determining the Optimal Role of Man and Allocation of Functions in an Aerospace System. This report provides methods and biotechnological data for determining whether or not man should have a role in an aerospace system and for determining the allocation of operator and maintenance functions to man if he has a role. The method and data are both articulated with the simple model documented in Report IA.

The content of all these reports is related to the simple model given in Report IA. The other reports amplify and enrich the simple model with more detail about biotechnological events which must occur, their order and relative importance to the Quality and Cost position of the eventual operational system (produced as the end product of development efforts). A more detailed discussion of each of these reports is undertaken next.

Report IA. A Simple Model of a Man-Machine Development Cycle

Report Requirements

In developing an aerospace system, it is important at frequent milestones to be able to predict the necessary development events that have not yet taken place, and to estimate the cost of that part of the development which remains. To estimate cost, ordinarily one must first predict the things which remain to be done which have cost associated with them. It is also mandatory early in system development to predict and thus to prepare for manning and equipping the design and production teams. Further, it is always desirable to be able to predict the supporting research and development activities that must be carried out in order to provide the required data inputs to enable development to progress in a timely manner. In fact, it is possible to continue to list many

occasions which require the prediction of the course of events that a development cycle should follow in order that it be carried out in an optimum way.

In the past, we have successfully developed many aerospace systems. If it is true that such predictions as those exemplified above are required in the course of any aerospace system development cycle, then how has the job of prediction been handled in the past? The answer is that we have employed crude models based upon our understanding of some of the commonalities which exist among development cycles and of how things have seemed to work best in the past. Because there are common features, someone who is familiar by experience with past aerospace system development cycles is able to set down (either implicitly or explicitly) a sort of model for a typical aerospace development cycle. It is necessary today to employ such implicit models because there is no satisfactorily detailed documented model useful for the purpose of prediction. To date, no model has been set down in the open literature where it may be subjected to examination and comment, and eventually to gradual improvement toward one that will truly meet the needs of managers of aerospace system development cycles. That is not to say that the literature is completely devoid of consideration of development cycles. Several authors in the field of system engineering discuss the general problem of the system development cycle and present brief characterizations of the process. However, most characterizations fall far short of the detail needed.

What is done today in the way of modeling for the purpose of enabling prediction is perforce makeshift. What is needed is a model in sufficient detail so that it can be used to improve predictive processes. If the first model has a sound basic structure, it will be possible for future efforts to build upon it. It is therefore desirable that a model be produced for the use of those system managers who must make predictions about system development, and that every effort be made to provide this first model with a sound framework. This report presents a model which has been developed in an attempt to satisfy this need.

The focus in this report is a biased one. First, emphasis is upon aerospace system development cycles. Second, in developing the model there was

more interest in serving the needs of system managers concerned with personnel products than the needs of hardware engineers. The model is thus designed primarily to satisfy a requirement for a model to enable personnel products oriented system managers to make predictions about the personnel products facets of an aerospace system development cycle.

Report Content and Uses

Report IA contains five key sections: (1) Conventions and Assumptions, (2) The Index Model, (3) The Development Cycle Model, (4) Use of the Model, and (5) Method of Developing the Model.

The section on conventions and assumptions presents the terms, symbols, conventions and concepts needed to evolve a technology of development cycles. New terms, and familiar terms with new meanings, have been developed in Report IA because there are not satisfactory terms in the vernacular for the concepts to which they refer, or because some words in the vernacular which are candidates for use appear to have so many alternative meanings that they might give rise to difficulty of interpretation on the part of the reader. This section defines a set of forty special-purpose terms used in the report series to describe the system development process.

The next major section concerns the description of an abbreviated version of the system development model called the index model. There are eight basic functions identified on this model to cover the more than 100 component functions in the complete development cycle model. The index model has two uses. First of all, it allows entry into the larger model by way of an introduction to the reader. Secondly, the brevity of the index model is intended to foster memorization by the reader. Each of the eight in-line functions comprising the index model represents a phase of system development to aid in referencing the larger simple model.

The third section presents the full development cycle model and the rationale by which it was derived from the index model. Each function or "activity" partitioned from each of the eight index model functions is described

briefly in terms of its output and its overall role in the success of the development cycle. The process of developing personnel products (i. e. , man in the system and his directly associated equipment) comprises the bulk of the activities within the development cycle model. As indicated earlier, the model has a biotechnological bias. The description and discussion of equipment development in the model is carried only to a level of detail necessary to place the development of man in the system in context. The model differentiates the part of the aerospace system which, when operational, does its work in the sky (or space) and those system means which remain remote from it (e. g. , on the ground). In the case of aerospace systems, the aircraft or spacecraft is referred to as the local segment, and that segment of the aerospace system which is remote from it is called the remote segment (be it on the ground or other location).

Report IB. A Simple Calculus for Discrete Systems

Report Requirements

The complex utility systems and weapon systems that are built out of public resources are basically problem solving systems; society buys them in the hope that they will serve to reduce needs that broadly affect society. As the larder of technology becomes better stocked and more sophisticated, society marks an unsteady course toward solving its problems by building new systems that are made possible by new technology. In recent times the fruits of science have become abundant and society has been building new systems at an accelerating rate. To some extent each new system builds upon the systems that have been developed in the past, and thus the overall size and complexity of systems tend to grow. With systems of ever-growing complexity, society has been able in recent years to solve problems that were not even deemed worth talking about in earlier times because the solutions to them seemed so remote. Thus, the importance of the new complex systems to society is great and there are strong pressures to continue to try to solve more and more of the problems of a society that is itself made increasingly complex.

With increasing complexity, and with increasing importance of the problems encountered, there has also been a trend toward increasing cost of systems. Thus, in our time new systems to serve society, such as waste management systems, power supply systems, and transportation systems require for their development such a significant proportion of our total resources that we cannot undertake them all at once, even though all are clearly within the scope of technology to build. Because of the high cost, there is need for capability to predict, to design, and to control development processes for the complex systems needed, so that our resources can be used most effectively to solve as many problems as possible.

In recognition of the importance of control over the development process, in recent years there has been increasing use of one tool that is useful for this purpose, the Program Evaluation and Review Technique called PERT. PERT was developed specifically to help solve the problem of gaining control of the development process and it does provide a partial answer to the need. However, the successful use of PERT techniques for the control of a given development cycle depends upon having an adequate description of the development process to be controlled. Given an adequate description, PERT techniques can be employed to redescribe the process in terms of resource requirements, time requirements, and contingencies, but without any description of the steps in the development process to start with, PERT is of no use. By the same token, a good PERT description cannot offset a bad process description upon which it is based. To date it appears that there is no generally available method for generating an adequate description of a development cycle so that a PERT description may be generated in turn and used to full advantage. There is a need for such a descriptive method.

There have been attempts to describe or model the process of complex system development. The most significant undertaking has been sponsored by the Air Force. With the support of the Department of Defense, the Air Force has prepared horrendously detailed description of the process by which the systems built under its aegis should be developed. However, the Air Force documentation does not lend itself to adaptation for solving the development cycle problem in general. It is tailored specifically for the management

conventions and hierarchical relationships of the Air Force. It presents a model for system development in great detail, but the model is not one from which general principles may be extracted, nor is it one that is easily amenable to evolution by means of rigorous public discussion. Several authors writing in the general area of system engineering have recently presented models of what the system development process is like; none of these contains sufficient detail nor adequate rationale for it to be useful for solving the problem of gaining control of the system development process.

Although existing documented descriptions of the development process are not adequate to enable the prediction, design, and control of development cycles for complex systems, they all demonstrate that the business of designing a development cycle is essentially that of finding a defensible strategy for the sequence and relationships of events that must take place in the course of developing a complex system. In order to talk about development cycle strategies without ambiguity, and in order to promote the comparison of alternatives in the course of evolving good strategies, we need a special language; specifically, there is need for a language whose terms and concepts are public and precise, and whose symbology is well-defined so that there can be an exchange of precise ideas between the specialists interested in the development process. Given such a language, there would be a good basis for communicating and improving development cycle models which exhibit useful strategies.

Report Content and Uses

Report IB presents a language which satisfies the needs outlined above. The language was generated within certain ground rules. A basic rule was that the language be useful for talking about development cycles. Another ground rule was that it be presented as a calculus according to the conventions of mathematics in order to take advantage of the established mores of the mathematical community as a way of providing for the orderly improvement of the language. Yet another ground rule was that the calculus should articulate with PERT and with probability calculus, such that it would permit building models of development cycles which could be translated into probability equations (models) on the one hand, or into PERT models on the other. This ground rule

was compatible with the objective that the language make it possible to utilize computers for testing and manipulating detailed development cycle models which might result from the use of the language. Finally, it was hoped to provide a language rich enough to enable the evolution and elaboration of relatively complex models of the system development process, should such elaboration prove to be necessary and fruitful.

The content of Report IB, then, is a simple calculus which serves as a language for talking about development cycles. It is called a "simple calculus for discrete systems," because we believe that any development cycle may usefully be treated as a discrete system.¹ In this manner, we have avoided the complexity which would have been necessary had we chosen to attempt the development of a calculus for systems whose individual outputs must be described over an interval of time, or whose outputs are distributed over time. Only the test of application will reveal whether or not this was a good decision.

The simple calculus presented in Report IB is for the reader who is interested in system development at a more theoretical (yet more precise) level than that portrayed in Report IA. Nine concepts basic to system development are rigorously interrogated and are precisely defined.

Report IB is organized into three sections. The first introduces the need for the calculus. Section two presents the list of concepts and the calculus plus a partial justification for the specific coinage and syntax chosen for the calculus. The last section relates the use of calculus in a brief manner to the description of system development cycles.

¹ A discrete system is one whose operation can satisfactorily be described as a sequence of events moving forward in time and whose terminal output state is fully described at a point in time after which no further events occur. Such a system must be one whose condition at any point of time can satisfactorily be described by stopping the clock and by identifying the complete condition of the system at that point in time. (Output state is precisely defined in the following section of this paper.)

Report IIA. System Development Activities Concerned With Putting Man in An Aerospace System

Report Requirements

Given that a system is to be manned (and all aerospace systems are, in one way or another), it is clear that there is a need to ensure that man is designed into aerospace systems in an optimal way. That is, the system solutions selected must employ man in a way that results in an operational system of high desirability measured in terms of overall quality and cost as compared with other system solutions. This report emphasizes that an optimal solution is one which is desirable as a whole; it is not one which has been suboptimized with respect to human performance (or any other system part or subsystem).

The development of an optimal system solution requires first that a strategy be created that will produce one. This is almost always difficult to accomplish. For one thing, such a strategy must take account of when man-related events should occur relative to the timing of other events in the development cycle. Of course, the timing strategy should be such that decisions are made neither so late that prior related decisions force a poor one to be made, nor so early that the decisions exclude subsequent desirable decisions. Therefore, we need a strategy for making design decisions which does not preclude the production of an optimal solution, but which promotes an optimal solution. A development cycle strategy to satisfy these requirements is presented in Report IA, discussed earlier. But while the model in Report IA defines such a strategy for man-related decisions in development, it does not provide information necessary for the design and control of each of the man-related activities per se.

Report Content and Uses

Report IIA is designed to meet the need which is not satisfied by Report IA. It is intended as an aid for planning and controlling each activity in an aerospace system development cycle which contributes to the production of

man-related end products, such as trained personnel, job aids, human-engineered interfaces and so on. To achieve this objective, Report IIA presents information about each man-related activity in terms of its purpose, its detailed relationships to other activities, and its organization.

The model of Report IA is not appropriate for the purpose of identifying who will perform the activities, what equipments are needed, and what disciplines and data must be brought to bear for each activity. It is in the description of the activities in Report IIA that these matters are considered. Further, the model presented in Report IA is a "GO" model; it does not take into account the technical management required to preclude, to detect, and to correct errors in the development cycle as it proceeds. In Report IIA, the description of each man-related activity departs from the "ideal" approach of the simple model and reconsiders, from a practical standpoint, what must take place in the real world of system development to produce personnel products.

We further find that, in the real world of system development, the manning and the equipage of certain kinds of development activities fall into natural groupings. Thus, several different activities might be accomplished essentially by the same personnel using the same equipment. It is therefore convenient to talk about those activities as a group. For this reason, the man-related activities identified in the model are organized into 13 activity groups. Each group is presented as a chapter and includes a prologue in addition to specific discussions of each of the activities in the group. The prologue to each group discusses the requirement for the group, the relationship of the group to the entire development cycle, and the personnel and equipment needed to perform the activities in the group.

Each activity group is sufficiently redundant in terms of identifying its relationship to the rest of the model to allow the potential user freedom from careful study of the remainder of the report. The write-up of the individual activity group, plus the system development model, provide for most of the user's needs for employing the activity group write-up as a guide. The main objective of Report IIA is to provide information useful in the planning and

control of activities related to putting man in an aerospace system, and it is anticipated that when it is used for this purpose it will be done so by persons primarily interested in a single activity group, or even in a single activity.

Report IIB. Development of Man-Machine Systems: Some Concepts and Guidelines

Report Requirements

The general discipline of human factors, with all its ramified sub-disciplines and splinter groups, has evolved a jargon peculiar to the design and development of aerospace systems. The terms and concepts developed have arisen from a need to communicate within the discipline and to have a basis for expression when studying and solving some of the man-related problems in the development of systems. These terms and concepts are, of course, in addition to those basic to system development, which are used extensively across disciplines.

Any new concepts which are introduced into the human factors encyclopedia, or any new terms which describe a new concept or a concept which has heretofore been described in some other manner, are slow to become accepted into human factors language. The creation of new concepts usually occurs either as a function of advancing technology for implementing them, or as a function of their never having been verbalized or heretofore made public. Terms originate in much the same manner. A new term which is merely a synonym for another term already in the repertory of human factors specialists stands little chance of acceptance. However, terms which do well for communicating new concepts, or are better able to communicate existing concepts, find the road to acceptance somewhat smoother. In any event, the proposition of a concept or a term should include a rationale as evidence to the potential user (however implicitly) that there is good reason to use the term in the future, and perhaps to reject others as a consequence. Even when this rationale is provided, acceptance is still often a slow process.

The report series (i. e., Reports IA and IB, IIA and IIB, and III) introduce and consistently use a set of terms, some of which are familiar to the

human factors specialist. However, many of the terms and concepts employed have new meanings for human factors specialists interested in aerospace system development. There is also an obvious absence of some terms and concepts quite common in the present human factors jargon, mainly because they have been subsumed within a new term or concept. The introduction of these strange terms and concepts was necessary due to the inability of some of the present vernacular to describe with precision and unambiguity the concepts put forth in this series of reports.

We face a large problem in attempting to present these terms and concepts in such a way that they will be accepted into the vernacular. What is required in order to do this is to provide the necessary rationale or justification, as discussed earlier.

Report Content and Uses

Since it is presumptuous to think that a new set of terms and concepts will be immediately accepted into the vernacular, it would be very useful as a first step to relate them to those which are already in the vernacular. Such an approach would give the reader the perspective he needs to evaluate for himself the worth of the new terms and concepts by comparing them to the vernacular and thereby demonstrating how they contribute to it.

Therefore, it was decided that the content of Report IIB should be a definition of the major terms and concepts used in the vernacular, many of which the Air Force has given birth to, plus a description of how the terms and concepts in the vernacular articulate with those put forth in the report series. Such an exposition provides the reader of the report series a means of entry into the vernacular and "out again" in order to better evaluate the worth of the contents of the report series.

To this end, a set of 27 well-known terms and concepts from the vernacular are discussed within Report IIB. These terms are considered under the following major concept headings:

1. Personnel Subsystem;
2. System Requirements Analysis;

3. Functions Analysis;
4. Design Conceptualization (Means Allocation);
5. Personnel Specifications Analysis (Task Analysis);
6. System Synthesis;
7. Human Engineering — Maintainability;
8. Personnel Selection and Training;
9. Personnel Subsystem Test and Evaluation;
10. Basic Design Data.

In addition, there is a section in Report IIB entitled Research Implications, which is a discussion of needs for providing greater clarity in aerospace system development terms and concepts evolution.

Report IIB affords the reader a chance to reexamine the vernacular objectively and determine for himself what there is in it which is not precise, and thereby ultimately to select for himself that set of terms and concepts which should, because of communicability, comprise the human factors vernacular of the future.

Report III. An Approach for Determining the Optimal Role of Man and Allocation of Functions in an Aerospace System

Report Requirements

Very early in the development cycle of each aerospace system a decision must be made whether or not to include man as one of the means by which the operational system will be implemented. A decision of this type is usually more important for the flight segment than for the remote base since man will probably always have some role in launching and recovery operations. When the system solution of choice does include a role for man, the next important step is to determine what man will do as a component means of the aerospace system. Identifying what he should do requires an effort generally known as allocation of functions. That is, since the value of the system lies within the services it can perform, there is need to identify specifically which of the

entire set of system functions man should be responsible for in order to obtain a system of superior quality within reasonable cost.

Therefore, there is a need early in system development to decide, first of all, whether man will be required, and secondly, if he is, what he should do. Subsequent man-related activities in system development are concerned with selecting, job-aiding, training, supporting, and human engineering for man in the system. These are consequences of the allocation of function decisions; they cannot make up for bad allocation decisions.

Despite the importance of being able to (1) define man's role, and (2) determine what he is to do in the system to be built, there is general concern among human factors and biotechnological specialists that good allocation of function decisions are not now being made. Specifically, we are not presently able to completely justify a role (or no role) for man in aerospace systems, and we cannot fully justify the determinations of the performances that are allocated to man when he is included in the system. The problems associated with making allocations are probably more severe with respect to the local segment than the remote segment. A review of current procedures in the literature for allocating functions reveals that there are two related needs which must be satisfied to improve the now imperfect allocation process: (1) a need for a public, teachable, generalizable method for carrying out the allocation of function decisions in a manner which fits the decisions properly into the total development process, and (2) a need for an organization of the supporting data used in making trade-offs during the decision-making process, so that data can be retrieved readily when needed. It appears that much of the data required are, in fact, available. The weakness of present methods of allocating functions appears to be that the data are indexed in a manner which makes them relatively inaccessible, thereby decreasing their utility.

Report Content and Uses

There are two major parts of Report III. The first is a model describing an effective strategy for both the determination of man's role and for carrying out the allocation of function decisions. The model is intended to be useful as

a guide for carrying out these decisions, and effort has been expended to the end that the model does not require unusual or unavailable background knowledge or data for its use. To render the model improvable, a rationale for its creation and use is included in Report III. The model contains 25 activities germane to the determination of the role of man and to allocating system functions to him. The activities are articulated with the system development model contained within Report IA. Each activity provides the user with information under the following headings: Outputs, Requirements or Constraints, Initiating Inputs, Input Data Requirements, Data Documentation Format, Method, and Research Needs.

The second objective of Report III is to present data necessary to support allocation decisions in a format which makes the data readily available as they are needed in the development process. Therefore, access to the relevant data is provided in a way that is compatible with the structure of the model to carry out allocation of functions. Further, the report contains appendices which include some supporting data for allocation of functions. Since the model and data are articulated with the total development cycle model of Report IA, it provides a way of integrating the decision-making activities into the system development cycle to ensure that the allocation decisions help to achieve a system which is optimum as a whole.

III. STUDY METHOD

The method by which the study was conducted is described diagrammatically in summary form in Figure 1. This figure presents an overview of the study in terms of twelve major tasks as it was conducted; it is a relatively minor variation of the plan prepared at the beginning of the study. The major difference between the study as conducted and the study as planned will be discussed in the description of the program which follows.

It is our objective here to describe the steps and rationale by which the study which resulted in Reports I through III was carried out. Such a report will provide one useful basis for evaluation of the study results. It may also be useful to others who wish to do further work in this field. The description of the study will be in terms of the twelve tasks identified in Figure 1.

In overview, it can be seen that Tasks A through F were all focused primarily upon the development of the basic model which was the output of Task F, and which was subsequently reported in Report IA. These six tasks were the core tasks of the study. They provided the basic information for the preparation of Reports I through III. Tasks H, I, and J (Reports IA, IIA, and III) were directly dependent upon the accomplishment of these core tasks. Tasks K and L are less directly related, as shown in Figure 1. We will first discuss the core Tasks A through F, which culminated in setting forth the basic development cycle model for manned aerospace systems.

As an interim step in the generation of the development cycle model, three prototype models were independently generated. Two of these were generated in Task D and one in Task E. Initially, the plan of the study was to integrate these three prototype models in Task F. The strategy in developing three independent prototype models was to reduce the probability that significant necessary development cycle events or interactions would be overlooked. By employing three independent researchers to develop three separate models, it was hoped to obtain models which could be cross-checked. Both of the models prepared in Task D were intended to account for producing a manned Mars system capable of scientific exploration. The objective in

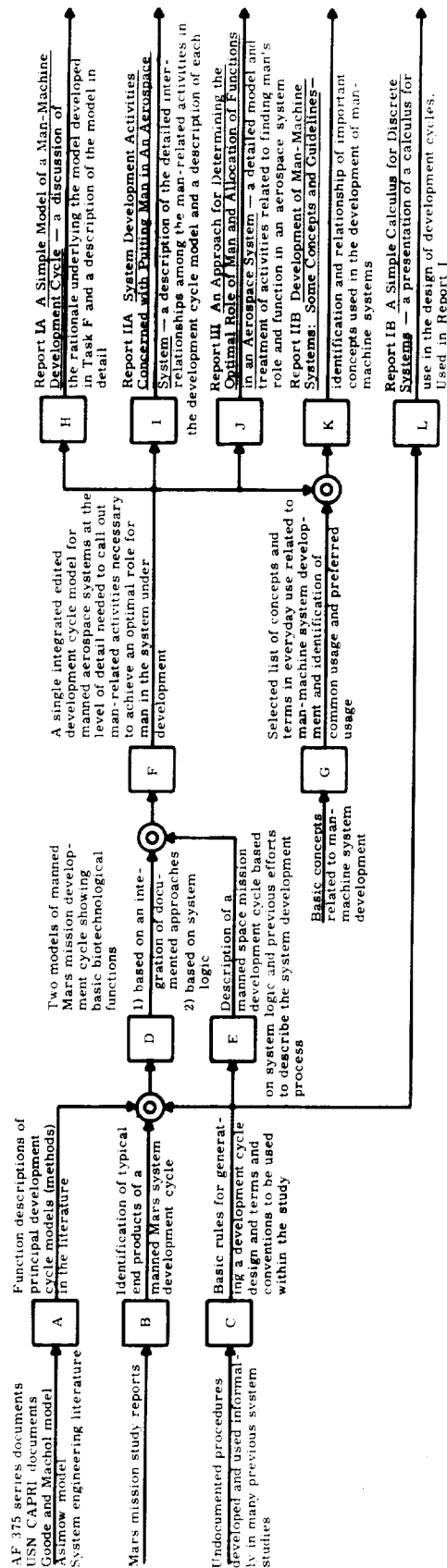


Figure 1. Relationships among major tasks of the study.

forcing these development cycle models into the mold of development cycles for a manned Mars system was to ensure attention to detail and to force consideration of real development cycle problems. The manned Mars mission was chosen because data at an appropriate level of detail were available relative to a mission of this type; another manned aerospace mission might have been as satisfactory for the purpose. One of the Mars models was developed on the basis of publicly documented information germane to development cycle strategy. By this method, consideration was given to existing information relative to the aerospace system development process in a context which forced an evaluation of current concepts. The second prototype model produced in Task D was generated on the basis of a logical analysis of the process required to develop a manned Mars system. Logical consistency and an explicit rationale were sought in this effort. There was no requirement to conform to established practice, as in the case of the model based upon documented approaches.

The third prototype model was developed in Task E. This model was based primarily upon earlier studies performed by Serendipity Associates which generated information relative to the processes of aerospace system development. The modeling effort in Task E was not oriented toward the development of a model specific to a manned Mars system, but rather the effort was directed toward the consideration of all types of aerospace systems, including aircraft systems. Specifically, information relative to what is known about the SST development cycle was taken into account.

The three prototype models produced in Tasks D and E were documented as "box and arrow" diagrams, with annotation presenting the underlying rationale for each. It is these working documents to which the output states for these tasks identified in Figure 1 refer.

Inasmuch as it was intended that the three prototype models be integrated to achieve a single model incorporating the best features of the three, there was need to provide some basic rules for common application to all three modeling efforts; otherwise, the end products might not have covered the same ground. The basic rules for generating the development cycle models were prepared in Task C. In preparing these rules, care was taken to avoid

providing so much structure that the three models would necessarily be highly similar. To achieve these objectives, two working papers were prepared in Task C. The first was entitled Outputs of Typical NASA Development Cycles. This working paper described the categories of outputs for which any aerospace development system cycle must account. Basically, the categories were categories of operational aerospace system means. The second working paper prepared in Task C was entitled Rules for Preparing Development Cycle Models. The paper included information under four headings: (1) Development Cycle Boundaries, (2) Major Subsystems, (3) Symbol Conventions, and (4) Assumed Development Cycle Outputs for a Manned Mars System. The last of these four sections of this paper was prepared as an output of Task B and will be discussed shortly. The first section identified the development cycle boundaries to be the Primitive Need Statement on the input side, and to be the delivery of an operational system with demonstrated capability on the output side. The second section partitioned the development cycle into three major subsystems in sequence: a definition phase, a design phase, and a development/production phase. This section also directed attention to the fact that the prototype model should contain only so much information about hardware development activities as needed to provide context for the specific identification of development activities related to man in an aerospace system. This section also directed that management functions be coded in the prototype models in such a way that the different prototype models might be compared after management functions were excluded. The symbol conventions section simply identified the symbols by which all of the prototype models should be described in order that comparison of the different models might be facilitated.

The symbol convention section of the second working paper was abstracted from an earlier working paper produced within Task C which informally described a basic calculus appropriate for application to development cycle modeling. This early calculus paper became a basic input to Task L as well as the basis for the symbol convention section. The informal calculus paper was an attempt to set down the system-descriptive language which has gradually been developing within the human factors/systems engineering technology.

To provide a common objective for the two models for a manned Mars system development cycle, effort was undertaken in Task B to develop a list of the typical end products of a manned Mars system development cycle so that the list might be employed in common as a definition of the output state of both Mars system models. The list of end products was derived by analysis of an abstraction from available study reports on manned Mars missions. The list of end products to be assumed was given in Section 4 of the working paper, Rules for Preparing Development Cycle Models.

The first of the two Mars system-related development cycle models was developed by integrating the best concepts available in the open literature. To provide for the development of this model, it was necessary first to identify the concepts to be considered and to document such development cycle model information as could be found. The symbol convention employed for this purpose is identified in Reports IA and IB. The open literature was surveyed for the purpose of identifying significant documents containing information about the development cycle process, and documents containing relatively complete models were selected for translation of the models into "box and arrow" form. Such models were prepared to represent the aerospace system development approach of the Air Force as presented in the 375 series documents, for the CAPRI approach of the Navy, and for the method of Asimow. Incomplete models were prepared, as appropriate, to document important concepts found in the system engineering literature when such concepts were not judged to constitute a complete coverage of the development process.

Tasks A, B, C, D, and E, which have just been discussed, developed all of the basic information necessary to undertake Task F, the task which produced the basic model of the study. Upon completion of Tasks D and E, it became apparent that no procedure could be found satisfactory to integrate the three models. The basic difficulty was that no criterion could be found for choosing parts from among the models such that a single superior one would result. However, at this stage in the study, the concept of the Cost, Quality space which is described in Report IA had not been developed. However,

the basic idea of Quality and Cost as criteria for selecting a system solution was contained in the second model, the one based upon system logic, and it became apparent that Cost and Quality taken jointly could provide a criterion for integrating all of the activities in a system development cycle. Therefore, the original plan of the program was changed and the second model was selected as a basic one from which to evolve the single model required as the output of Task F. The rationale for the second prototype model was rather fully described in a working document, and the prototype model was then evaluated by two independent system engineering experts¹ for the purpose of determining whether or not it was inconsistent with the realities of what must be done in system development. Evaluation was also for the purpose of determining whether or not changes might be required to ensure logical consistency or to take account of significant ideas known to the engineering community. The prototype model stood up well under this scrutiny and it became the basic model which was reworked and elaborated in Task F.

Two kinds of changes were then made in the prototype model: (1) the strategy for the first phase was thoroughly reworked to provide for the development of Cost and Quality criteria for Phases II and III; (2) provision for Cost and Quality criteria having been set forth in the specification in the output of Phase I, Phases II and III were organized in such a manner that the criteria could be applied consistently throughout these phases to guide the development process. The sense of the development cycle model which resulted was one in which the first phase focused upon the development of a single set of criteria for all steps in Phases II and III such that designs as well as end products might be tested against a common set. This approach tended to ensure the efficiency of the development process because it provided for intermediate design steps to be tested against the same criteria as the development cycle output and thus tended to ensure that intermediate steps would be directed toward achieving an acceptable output.

¹ Dr. Warren E. Wilson of Harvey Mudd College and Dr. Elliott Axelband.

The model which resulted was consistent in its internal logic and its logic was public in that it was made explicit in a set of notes. The model was then tested in several ways to determine whether or not it was comprehensive. Thus, it was compared with the other two prototype models for the purpose of determining whether or not either of these provided for essential development steps not encompassed in the model being evaluated. Similar checks were made against the models taken from the literature and expressed in the output of Task A. These checks resulted in only minor changes. No new activities were added as a result of these checks, nor were major relationships among the activities changed. Some output states were, however, amplified and made more explicit. The model was then checked for completeness of coverage against a special card file. The card file was prepared from a wide variety of documents, including textbooks, specifications, regulations, and so forth. These sources were screened and a card was prepared for each described or implied activity related to determining the role of man in complex systems. The card file, as initially developed, contained over 600 items, with unknown redundancies. The file was then checked by a method which employs a test matrix for the purpose of determining if there are empty cells when the contents of the card file are allocated in the matrix. The columns in the test matrix identified categories of man-related products of a system development cycle and the rows identified types of contribution of man performance to aerospace system performance. The result of the test was that meaningful empty cells identified gaps in the coverage of the card file. This directed attention to new sources of stimulus materials from which the gaps were filled. The augmented card file was then used to test the model to determine whether or not there were gaps of coverage in the model. The result of this check was to improve further the output statements in the model.

When changes had been made as a result of the checks on the content of the model, these were set down in symbolic form and comprehensive notes on the underlying rationale were prepared. The model in this form was then employed as the key basis for the preparation of the final reports.

Task H was the first of the research report tasks. In this report, the full rationale for the model was set down. To provide a basis for precise

communication of the rationale, over three dozen special concepts and terms developed in the course of the study were described so that they might be employed in all of the research reports. Many of these terms were drawn from the early calculus paper developed in Task C. As presented in Report IA, the definitions of these terms provided an intuitive understanding of the principal terms in the calculus of Report IB. The group of concepts necessary for talking about the Cost, Quality space was also defined. Report IA was then organized about a presentation method which was designed to introduce the reader gradually to the full detail of the aerospace system development cycle model.

Task I was concerned with the preparation of Report IIA, the report which presents detail with respect to those activities in the model of Report IA that are specifically man-related. As the model was developing in Task F, the man-related activities began to be identified and a literature review was undertaken in anticipation of the task of preparing Report IIA. A study was undertaken of how man-related activities in development cycles are organized and related to each other in common practice. This provided a basis for organizing the activities identified in the model into meaningful groups, so that they might be treated in Report IIA by group. The model presented in Report IA identified only the major outputs of activities and the initiating input of each. This avoided undue complexity in the model of Report IA, but at the same time tended to occlude many of the relationships among activities necessary in the prosecution of a real-world development cycle. To prepare for Report IIA, study was therefore undertaken of the detailed relationships among man-related activities and between man-related and hardware-related activities. This analysis became the basis for the key feature of Report IIA; and thus Report IIA became an extension of the model given in Report IA. On the basis of these analyses and a final determination of how each group must be related to the model as a whole, the preparation of Report IIA in its final form was undertaken.

The complexity of Task J is not shown in Figure 1, which is a simplified representation of the study approach. The objective of Task J was to prepare Report III, and the final preparation of this report required that the model expressed in the output of Task F be available. However, Task J was in fact

initiated well before the completion of Task F in order that Report III might be prepared quickly once the Task F output was available. Task J was initiated by consideration of the process by which it is determined whether or not man will have a role in a given aerospace system and of the process by which his specific role is determined when he is to have one. Two sequential related models were developed, and when the output of Task F became available, they were modified and articulated with it to provide for more detailed consideration of the role-determining process and of the allocation-of-function process than was provided in the overall aerospace system development cycle model. The two models prepared in this manner were the principal grist for Report III. They provided the basis for identifying component activities which were then described for inclusion in Report III.

Simultaneously with the development of the role and allocation models, a literature search was begun to identify the basic data required as inputs in the course of carrying out the activities identified in the models. As the models took form, a scheme for organizing the available literature was developed to provide for the ready access to information by means of entries which derived from consideration of the development cycle process rather than from consideration of the disciplines involved in the generation of the data. The background data were then organized and prepared as appendices to Report III. These appendices provided a framework for the future organization of new data and they provided a key pool of data organized in a manner to assist the human factor specialist in carrying out role determination and allocation of function activities in a specific aerospace system development cycle.

Task G was preparatory to Task K. The output of Task K was Report IIB, a presentation and discussion of the important concepts used in the everyday world of man-machine system development. Task G was concerned with the review of the concepts in use in talking about and implementing man-machine system development and with selection of those which should be considered in Report IIB. In Task G, the literature was reviewed to identify common usage and preferred usage. In Task K, these concepts were related to key super-ordinate concepts which became chapter headings in Report IIB. To prepare Report IIB, each concept was developed by describing the manner of its use

in the vernacular. Concepts were discussed and related to the special terms and concepts presented in Report IA.

Task L was based primarily upon the informal "calculus" paper prepared in Task C. This paper was reviewed and interpreted in mathematical terms by an independent expert.¹ The basic concepts were then given formal meaning in mathematical terms. Report IB was prepared after a final check against the content of Report IA to determine all of the needs for the calculus.

¹ Dr. Alden F. Pixley of Harvey Mudd College.

IV. IMPLICATIONS FOR FUTURE WORK

In this section we consider the implications of the study from the standpoint of what needs to be done further to improve the utility of the results presented in the research reports of this series. Coverage here is restricted to the consideration of implications of the study as a whole; research requirements related to specific topics in biotechnology and human factors are considered in Reports IIA, IIB, and III as appropriate to the major topic of each. Five major requirements for research are discussed. Each is identified in terms of the underlying requirement and in terms of the end product which should be produced by future research to satisfy the requirement.

1. Development of Techniques for Determining When to Select a Preferred System Approach in a Complex System Development Cycle

Need for the Study

Let us suppose a system is proposed which meets a genuine requirement to a satisfactory degree. Let us further suppose that the system requires only current technology and that good cost estimates indicate that it can be acquired within budgeted funds. Should development of the proposed system proceed? The answer is, "Not necessarily." In general, we should first determine that there are not significantly better alternatives. What is needed is a technique by which we may know when a proposed system solution is so "good" that we are unlikely to find a more desirable alternative without undue expenditure in the search. At present, the selection of the preferred system approach is made primarily on the basis of an informal procedure based upon engineering evaluations of several alternatives for the purpose of finding the best among those considered. Even when diligent effort is made to decrease the chance that good alternatives have been overlooked, the selection of one of the alternatives may still be primarily an act of faith. Thus, if we were asked in such a situation, "What is the likelihood that we could find a system with the same quality as the best alternative in the group but at half the cost?," in most circumstances a satisfactory answer could not be given.

What is needed is a set of practical techniques to enable system designers to determine when a proffered solution is sufficiently desirable that better alternatives are unlikely to be found.

Study End Product

To satisfy the need identified above, a study is required that will focus upon investigation of the characteristic nature of the cost, quality space for any given system, and that will result in the identification of practical techniques which may be employed early in the development cycle to estimate the distribution of solutions in the cost, quality space for the system under development. Given a technique for estimating the distribution of solutions in this space, it will be possible, in general, to determine the likelihood that a solution can be found that is better than one of a given cost and quality.

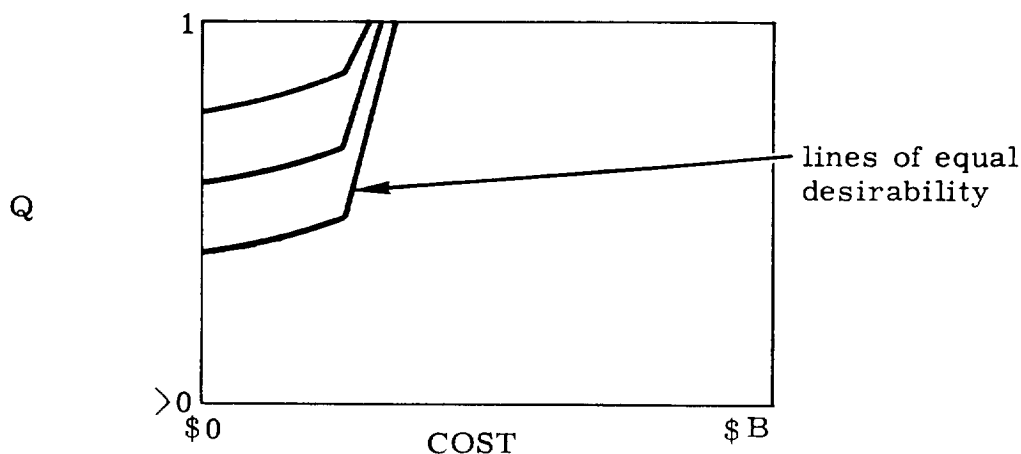
To identify the needed end product more precisely, it will be useful briefly to consider the nature of the cost, quality space and the relationship of cost and quality to another characteristic of systems which we will call desirability.

Since we are concerned with finding "better" systems, we must have criteria for comparing likely system solutions. We will restrict our consideration here to the comparison of systems in terms of criteria which may be applied to all system solutions in a given cost, quality space. Thus, we will set aside for consideration elsewhere problems of comparing systems in terms of the fortuitous, desirable, and undesirable effects of system solutions themselves.¹ Let us assume that measurements of quality reflecting the goodness of system solutions are expressed on a numerical scale ranging from >0 to 1, 1 standing for perfect goodness. Let us assume that measurements of cost are expressed in terms of the total dollar value of all resources necessary to design, develop, install, operate, and maintain a system which belongs to the solution family under consideration. Then a particular system

¹ See the concept of "A" scores in Report IA.

solution takes, by virtue of its cost and quality attributes (estimates), a specific position in a cost, quality chart. Now if we had cost and quality estimates for every conceivable system solution which might be proposed to satisfy the requirement for the system, then the cost, quality chart would become literally covered with points. We know from experience that there are going to be more systems which fall in the low quality-high cost part of the chart than in the high quality-low cost part. The exact distribution of the systems in a given chart depends upon the specific nature of the system requirement and the state of the art.

A system's position on a cost, quality chart fixes its desirability. Two systems which differ in cost and quality are said to be equally desirable if the customer for the systems cannot discriminate between them by saying that he would prefer to have the one over the other. With the help of the customer for a given system, it should be possible in concept to overlay a cost, quality chart with lines of equal desirability. For example,



Any two points on the same line are equally desirable, and given two lines, the one which is farthest to the left touches system solutions which are more desirable than those touched by the other line. The lines of equal desirability thus show a customer's preferences in a quality versus cost trade-off.

If we had sufficient information about the distribution of systems in the cost, quality space, it would be possible for any given line of equal desirability to state the proportion of all system solutions in the space lying above and to the left of the line. Given the capability to calculate such proportions, we would have a basis for deciding for any given system solution lying on a given line of equal desirability the proportion of solutions that are more desirable and we would thus have a basis for deciding whether or not to seek a better solution.

It must be recognized that each time we turn our attention to a different system requirement, we get a different cost, quality chart. What is needed, then, is a general technique for estimating the distribution of system solutions in any cost, quality space with sufficient precision to enable useful estimates of the chances of finding better solutions, given a solution in the space. The end product may best be described as a set of instructions which will tell how to construct the chart to reflect the cost, quality distribution for any system requirement.

If we knew nothing about the typical distribution of system solutions in a cost, quality space, obviously it would be necessary to find a rather large, unbiased sample of the solutions in a given space in order to obtain an estimate of the distribution of solutions. Inasmuch as the estimation even of crude quality and cost attributes of a given system solution is a rather expensive process, such an approach is not likely to be a practical one. Fortunately, we may reasonably expect to find that general statements can be made about the distribution of solutions such that fair estimations of distribution may possibly be made on the basis of a relatively small number of data points. For one thing, there is good reason to suspect that the contour lines in the cost, quality space are growth curves. If we can show that the contour lines which describe the changing density of solutions in a cost, quality space may be fairly described by growth curves, then we will be able to capitalize upon our mathematical understanding of these curves as an aid to estimating solution densities in a given space. The end product that is required, then, is a set of techniques for estimating the density of solutions in any given cost, quality space on the basis of information which may be generated within reasonable time and dollar costs.

2. Extension of the Development Cycle Model to Include Improved Detail with Respect to Hardware-Related Activities

Need for the Study

The need for the model developed in the present study was presented with a biotechnological bias. Thus, the model presented in Report IA was designed primarily to provide information useful to those system developers concerned with man's role in the system under development. In generating the model it was necessary to consider grossly the hardware-related activities which parallel man-related activities in the course of development. Consideration of hardware-related activities was restricted, however, to the level of detail needed to identify and provide context for the man-related activities. The model as it stands in Report IA is thus out of balance with respect to detail. While sufficient information about the general strategy of system development is presented in Report IA to provide gross guidance for hardware-oriented system developers, the model falls far short of presenting the amount of detailed information and strategy that is desirable. What is required is an extension of the model to include commensurate detail with respect to hardware-related activities in system development. Such an extension not only would serve to provide a better context for the man-related activities, but would also provide a basis for designing a complete development cycle, including hardware- and man-related activities. By providing for complete support for the process of development cycle design, the quality of aerospace system development cycles in general might be improved, and the likelihood of use of the model would be increased. As a by-product, use of the overall model would provide a proper context for carrying out man-related activities.

Study End Product

With the assistance of experts who have practical experience in conducting development cycles for complex aerospace systems and who have top-level experience in the design of such development cycles, a study should be

undertaken to extend the model of Report IA to include commensurate detail with respect to hardware-related and man-related activities. The study output required is a complete symbolic model and an exposition of the rationale underlying it. In order that the end product may find acceptance and use, it should be presented in such a form and in such a language that system managers will be willing and able to use it. Inasmuch as it can be anticipated that use of the model will require the user to learn certain new concepts and techniques, the end product of the study should include an effective didactic device that may readily be employed by interested managers to learn the necessary background in preparation for using the model. A 16 mm sound film might, for example, be considered as a medium for presentation of the concepts which must be learned. The presentation of a "cookbook" model which cannot be modified on the basis of learned principles relevant to system development is to be avoided, for such models do not lend themselves to improvement by evolution. Further, if a cookbook model contains sufficient detail to be useful, it is likely to be one that can be used only if it is committed to memory by a tedious rote-learning process. A model which is based upon a learnable rationale and common logic may, on the other hand, be relatively easy to learn and to reproduce, and may thus more readily be accepted by system managers as a practical tool.

3. Principles for Developing a Quality Score Formula for an Aerospace Science Mission

Need for the Study

Some aerospace flights are undertaken for the purpose of developing aerospace technology and the data which are gathered by means of such flights may be called engineering data. Even such flights, however, are preparatory to other flights which focus upon the gathering of scientific information. Thus, we may say (deliberately excluding from consideration propaganda effects) that aerospace missions in the foreseeable future will all be science-oriented. All will be oriented primarily toward obtaining information to be added to that public data pool which is the content of science.

In generating the development cycle model that is presented in Report IA, the need for a single criterion to be employed throughout the process of system development to evaluate all stages of development was clearly seen. Three kinds of criteria were identified: (1) Quality score criteria, (2) Cost (resources) criteria, and (3) "A" score criteria. The first two of these may be set forth without considering the means by which the system requirement is to be satisfied. The second, the cost criterion, is one which we are relatively well prepared to develop and apply; the first, the Quality score, is one for which we are not so well prepared. To provide for the effective use of Quality score criteria in the development of future aerospace systems with scientific missions, it is desirable that principles with respect to the preparation and use of such Quality scores be developed and made available. By making available such principles, a technique would be provided for improving decision-making in the course of aerospace system development and a basis would be provided for promoting general understanding with respect to criteria and objectives in aerospace system development. All of these effects could be expected to improve future programs significantly.

Study End Product

If we think of a Quality score as a number in the interval $0 < Q \leq 1$, then the end product of the needed study must at least identify the mechanical techniques necessary to estimate a Quality score for a given mission. In fact, however, if one seeks to set forth such "mechanical" techniques, it rapidly becomes apparent that several other questions must be answered first. The basic underlying question to be faced is the question of what is to be measured in order to develop the basic data necessary to compute Q . There is a tendency in the literature to speak as though the purpose of a mission is to conduct experiments, implying that Q should be based upon whether or not specific experiments were conducted and upon the success of those which were. In fact, however, consideration should be given in the study to the point of view that Q should be based upon the number and goodness of scientific answers obtained, and that, before the fact, a mission should be designed against a criterion in terms of answers required. A principal reason for

developing Q on the basis of answers rather than experiments is that some desired answers may be obtained by alternative experiments, thus to call out a science system in terms of answers is to leave open to the discretion of the designers the experiments to be conducted. Such a course gives desired freedom to the designer and makes it possible for him to select, within weight restrictions, the set of experiments for a mission that will give the most desired set of answers.

Not only must the end product of the study consider what is to be measured in order to estimate Q for a given system, but it must also consider how the various measurements obtained are to be combined to obtain the single number which expresses Q for the system as a whole. Ordinarily, it will be desired that a given mission gather many answers, and most frequently the number of answers desired will be greater than the number that it will be possible to obtain because of state-of-the-art limitations, for example. The study must therefore consider how the measures of goodness of individual answers are to be combined in a Quality score formula. One basis of combination to be considered rests in the conjecture that the relation between the number of answers and Q for any system is given by a growth curve.

Whatever the relation between any set of answers and Q for any given mission, the relation must be presented in a form that will enable the use of Q , first, to guide the process of system development such that maximum quality commensurate with available resources will be provided for in design and, second, so that criteria will be available during the course of system operation to permit continuous adjustments based upon data feedback so that maximum quality will be obtained.

Without a better general understanding of Quality score criteria for aerospace systems, there is danger that the engineering orientation necessary early in the history of aerospace systems work will continue to predominate at the expense of achieving maximum scientific return by the optimum use of resources available for aerospace systems work.

4. A Study of Management Techniques for Insuring Maximum Development Cycle Quality

Need for the Study

In the design of complex systems one strives to achieve a system solution in a desirable cost, quality position. Usually, the Quality score formula for a complex system includes consideration or probability of system success as an important element in quality. Therefore, most system designs must incorporate provisions deliberately and selectively focused upon achieving overall operational system performance that is reliable to a specified degree.

One may conceive of a development cycle itself as a system just as one conceives of the end product of the development cycle as a system. And just as a Quality score is necessary to provide for the evaluation of the operational system that is produced by a development cycle (including evaluation of the reliability of the operational system), so must a Quality score be set down to provide a basis for achieving a reliable development cycle. In Report IA, the Quality score for a development cycle was called Development Q (Dev Q). The formula for Dev Q for any development cycle must always include consideration of the quality of the operational system that is produced. It will most often include also consideration of the time and resources required to prosecute the development cycle, and it may even specify that the output of the development cycles occur neither before nor after a given target date.

The concept of probability of success of a development cycle is important in estimating the goodness of a development cycle after it has been designed but before it has been carried out. Development cycles with low estimated probability of success are, in general, less desirable than otherwise similar development cycles with high probability of success. Because of the importance that is usually attached to probability of success of a development cycle, provision is needed to enhance probability of success. In Report IA, a basic "GO" model of a development cycle was presented which did not consider provision for probability of success. In a final chapter, some principles were set forth by which such a "GO" model might be elaborated to provide

for high Dev Q, including high probability of development cycle success. The principles discussed were dubbed "management" principles. Basically, the principles described were derived by generalization of the techniques commonly employed to provide for high probability of success in operational systems; the techniques were not derived on the basis of consideration of the extant management science literature. What is needed is a study to extend the principles which may be employed to achieve high development cycle quality to include all that is useful within the current state of the art of management science. It can be expected that such an effort would materially increase the utility of the model presented in Report IA.

Study End Product

The end product that is desired should present what is useful within current management science in terms that render the management concepts compatible with the concepts upon which the development cycle model of Report IA are based. Basically, the end product must be the result of a filtering out of those management concepts which are too imprecise to be included within the rationale of the development cycle model. This will require a rather complete survey of current management practices and ideas which are publicly documented and an attempt to translate each so that it may be expressed precisely in a manner compatible with the present model. It may be expected that many of the ideas found will not lend themselves to precise expression. Some of those which do not may be rendered more precise; some will have to be rejected as unsuitable for application. It is also possible that ideas may be uncovered that will reveal the need for basic changes in the present model. Such findings would be of most importance, and the study end product should give specific attention to them and to the consequent recommendations for change in the model. Otherwise, the end product that is desired should be an expansion of Chapter 5 of Report IA to include a comprehensive coverage of techniques useful for elaborating a development cycle design to the end of providing for high development cycle quality.

5. Restudy of Human Factors and Biotechnological Specializations for the Purpose of Relating Them to Cost and Quality Criteria for Operational Aerospace Systems

Need for the Study

Human factors, biotechnology, human engineering, life support system technology, and all the related and component areas of specialization have developed in relatively recent times. These areas of specialization which relate to the business of putting men in complex systems, are all difficult to define discretely. When attempts are made to define any one of them, it is found that clean lines of demarcation cannot be drawn and that each overlaps a good deal with many others. This is so because in ordinary usage we think of each of these specializations as encompassing content, type of technical activity, and special desired effects. Because each of these areas of specialization is fuzzily defined, we are frequently at a loss to identify appropriate criteria by which the activities carried out in the name of one of these areas of specialization may be evaluated in the course of a system development cycle. Thus, it is often difficult to say precisely how a human engineering group will be evaluated when such a group is employed to assist in the prosecution of an aerospace system development cycle. When a manager is unable to say how he will evaluate the activities of such a group, he is also unable, by the same token, to identify the work which they must do. In this kind of management void, such special groups develop criteria of their own and extend their interests along activity lines, along content lines, and along effect lines, until it is no longer clear, if indeed it ever was, how they relate to the overall objective of a system development program. Here and there we can find rationally acceptable reasons for their existence and so we support them in the hope that those activities which are not well understood may also be justifiable.

Not only is there frequently an inability to specify what a specialist group must do, but there is also frequently an inability to justify the total proportion of resources to be allocated to a specialist group, such as a life support

system design group, for example. Clearly, what is needed is a way of developing criteria for the activities of such a group to the end that the group output may be evaluated in terms of its contribution to system quality, and in terms of the cost of its contribution as compared to the total cost of the development program. The development cycle model presented in Report IA provides an elementary basis for achieving these objectives. The discussion of man-related activities in Report IIA provides a further basis for the development of the needed criteria. However, present conceptions of the various areas of personnel products related specialization, are at variance with the conceptions of activity groups presented in Report IIA. So, therefore, is the supporting technical documentation for each specialty area at variance. Before it will be possible to make significant headway in orienting development cycle activities such that cost and quality criteria are employed, it will be necessary to reorient the basic data and the practitioners of each major specialty area. What is particularly needed, therefore, is a systematic review of each specialty area in terms of activity requirements as set forth in the development cycle model. Any such undertaking would require a relatively large investment in technical and dollar resources. In view of the poor basis for management of development cycles and consequent high cost of development which are the penalties for not making the undertaking, it may nevertheless be justified in spite of its high costs.

Study End Product

A similar end product is desired for each of several activity groups. The groupings of activities for this purpose may be the groupings employed in Report IIA of the present series, or alternative groupings may be developed after further consideration of the basic development cycle model. However the grouping is accomplished, it should be consistent with the rationale of the development cycle model so that criteria for activities may be developed systematically on the basis of overall system cost and quality criteria. For each activity group, technical documentation is required that will be made broadly available and that will be written in language such that it may be used by any properly trained technical person in the area of specialization

of the document. Each document should consider the manner in which criteria for the activities within the group under consideration should be developed and applied in the course of development cycle design and prosecution. Each document should discuss the manner in which activities within each group may be managed technically for the purpose of maximizing activity contribution to overall system cost and quality objectives. The document should incorporate the information relating activities that is presented in Report IIA. In selected cases, technical appendices should be developed that would yield technical data pools reorganized in a manner to provide for the ready retrieval of information needed in the prosecution of the development cycle activities under consideration.

6. Study of an Information System to Support Man-Related Activities in Aerospace System Development

Need for the Study

In every aerospace system development program there is need to use some of the existing data which relate to the attributes of man. Currently, these data are found in a great amorphous pool which includes information in the open literature and private information. While not every development program requires the same data, there is much overlap of usage from one program to the next and it is necessary that time and energy be expended in the course of every development cycle to "fish" in the existing pool.

To repeat the setting up of procedures to retrieve existing data for each development program does not represent a good use of resources. But the present state of the data pool probably has an even more harmful effect than the wasting of resources, for the difficulty associated with the retrieval of needed information must frequently dissuade designers from using existing data. In fact, often data are not even sought because their very existence is not recognized. What is needed is a system which enables the ready identification of the data that must be consulted in the development of aerospace systems for the purpose of promoting the optimal use of man.

The exercise conducted to collect and organize the data presented as appendix materials to Report III of this series uncovered the need discussed here. Even though this exercise encompassed only a small portion of the total relevant data pool, and even though no attempt was made to uncover all data in the restricted area of concern, the identification, collection, abstraction, and organization of the data presented required several months of calendar time. While the application of greater resources might reduce the calendar time required for this exercise by some amount, it does not appear that savings in time could be achieved that would reduce the process to one which could be carried out as a timely adjunct to a specific system development program.

Study End Product

Satisfaction of the need identified above might involve the design, fabrication, installation, and operation of a rather complex data storage and retrieval system. On the other hand, it might be found upon careful analysis that the cost of satisfying the need by means of such a complex solution would not be justifiable. What is needed at the outset, therefore, is not a detailed design for a solution, but rather an objective detailed description of what the needed system should do and a complete report of the benefits and penalties that will be realized if a system is developed in response to the specification of what it must do. Thus, what is needed is a specification identifying the problems the system must solve, identifying how entry to needed data must be gained by system users, and identifying how any implementation of a system would be evaluated.

In the study underlying Report III, it became apparent that provision must be made to gain access to the biotechnological data by the use of system-related terms as opposed to terms in the biotechnological discipline. Entry by means of such terms is not now possible. The end product of the required study should therefore identify in detail an appropriate entry procedure along with rules for expanding the procedure in the future. The end product should also identify the classes of biotechnological information germane to each system-related entry so that the classes of data to be sought are clearly

identified. Such information would provide a basis for a third end product,
an estimation of the cost and utility of a system to provide ready access to
the classes of biotechnological data identified.

Serendipity Associates,
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